Destructive Single-Events and Latchup in Radiation-Hardened Switching Regulators

Sergeh Vartanian, Gregory R. Allen, *Member, IEEE,* Farokh Irom, Leif Z. Scheick, *Member, IEEE,* Shirley Hart, Nick W. van Vonno, *Life Senior Member, IEEE,* and Larry Pearce

***Abstract*—Single-event destructive behavior and latchup has been observed in two separate radiation-hardened switching regulators. We discuss the test conditions and observed results.**

***Index Terms*—Single Event Latchup, Single Event Hard Error, Switching Regulators, Heavy Ion Testing, Single Photon Laser Testing**

I. Introduction

THIS paper reports the results of single-event effects (SEE) testing of the Intersil ISL78843ASRH and Linear Technology RH3845 radiation-hardened switching regulators. In the case of the RH3845, which is built on a 4um purely bipolar technology, voltage dependent, destructive SEE were observed. For the Intersil device, temperature and voltage dependent single-event latchup (SEL) was observed during heavy ion broad beam testing and verified on a single photon absorption laser system. The objective of these tests was to develop a baseline hardness evaluation of switching regulators for an SEE environment for use in JPL missions. Test setup, conditions, results, and radiation-hardness assurance (RHA) implications are discussed.

II. Device information

A. Linear Technology RH3845

The RH3845 is a radiation hardened, high voltage, synchronous, current mode, step-down controller for high power and efficient supplies with a total ionizing dose (TID) tolerance of up to 200 krad(Si). It offers an operational input voltage range of 4V to 60V (requires minimum of 7.5V at start-up), an onboard regulator providing IC power directly from V_{IN}, and output voltages up to 36V. Additionally, this device features adjustable fixed operating frequency (100 kHz to 500 kHz), power MOSFET gate drivers, undervoltage lockout, low shutdown current, and short-circuit protection. Linear Technology provided the RH3845 as-is, packaged in a 20-pin ceramic narrow dual-inline package (DIP) [1]. The part is also used as the switching regulator in the MSK5055RH regulator [2].

B. Intersil ISL78843ASRH

The ISL78843 is a radiation hardened, high performance, current mode, PWM controller. The device features include 1A MOSFET gate driver, low start-up and operating currents, fast transient response, and adjustable switching frequency up to 1 MHz. The operating supply voltage ranges from 9V to 13.2V, with an absolute maximum of 14.7V; the operational temperature ranges from -55°C to 125°C. Intersil provides this device in two different packages; the parts tested were packaged in 8 LD flatpack packages [3].

III. Experimental Procedure

A. Test Facilities

1) Heavy-ion Facility

The heavy ion SEE measurements were performed at the Texas A&M University (TAM) cyclotron, which provides a dedicated heavy ion beam with wide range of ions and energies for SEE testing [4]. Generally speaking, tests were performed in accordance with JESD57. All tests were performed in air. Particle fluence per exposure was typically $1x10^5$ cm^{-2} to $1x10^7$ cm^{-2} with a flux adjusted for the observed event rate, nominally between $1x10^3$ cm^{-2}s^{-1} to $1x10^5$ cm^{-2}s^{-1}. Beam uniformity was greater than 90% in all test cases. The list of ions used for the RH3845 and ISL78843 experiments are shown in Table I and Table II respectively.

TABLE I
List of ions used for the RH3845 SEE measurements.

Ion	Initial Energy (MeV)	LET (MeV-cm2/mg)	Range (µm)	Incident Angel (Deg)
^{109}Ag	1289	42.2	120	0, 60
^{84}Kr	1032	27.8	134	0
^{63}Cu	785	19.6	135	0

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

S. Vartanian is with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA (phone: 818-354-0311; e-mail: sergeh.vartanian@jpl.nasa.gov).

G. R. Allen is with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA (phone: 818-393-7558; e-mail: grallen@jpl.nasa.gov).

F. Irom is with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA (phone: 818-354-7463; e-mail: farokh.irom@jpl.nasa.gov).

L. Z. Scheick is with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA (phone: 818-354-3272; e-mail: leif.z.scheick@jpl.nasa.gov).

S. Hart is with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA (phone: 303-819-1527; e-mail: shirley.hart@jpl.nasa.gov). Author is currently a contractor at JPL; she performed this work while she was employed at Linear Technology Corporation.

N. W. van Vonno is with the Intersil Corporation, Palm Bay, FL 32905 USA (phone: 321-724-7546; e-mail: nvanvonno@intersil.com).

L. G. Pearce is with the Intersil Corporation, Palm Bay, FL 32905 USA (phone: 321-729-4030; e-mail: lpearce@intersil.com).

TABLE II
List of ions used for the ISL78843 SEE measurements.

Ion	Energy (MeV)	LET (MeV-cm2/mg)	Range (µm)	Incident Angel (Deg)
^{109}Ag	214	41.5	125	0, 60
^{181}Ta	193	76.4	124	0, 27, 50, 60

2) Laser Facility

The laser measurements for the ISL78843ASRH were performed at Jet Propulsion Laboratory using JPL's laser system that incorporates a broadband tunable Spectra-Physics Ti: sapphire mode-locked Tsunami laser (picosecond version) pumped by a Millennia Pro5s laser with a 5W CW output at 532nm. For this particular experiment, the wavelength was set to a value of 750nm so that an assumed collection depth around 10µm (approximate absorption length in Si) could be achieved [5]. The laser spot, which is 1µm full width at half maximum, was focused on the DUT with an energy of about 100pJ.

B. Bias Conditions and Test Levels

1) RH3845

For this experiment, we did the design, layout, cutting, and fabrication of the test board (DUT card) in-house based on the schematic shown in Fig. 1. This allowed precise voltage control and latch-up detection and protection once powered through our SEE power supply and software. Using two channels from the Agilent N6700B power supply, we first provided 5V to the active low Shutdown pin and a variable input voltage for the V_{IN} pin, which can be varied between 4V to 60V. For our SEE measurements, we started at V_{IN} set to 20V and increased it to 30V and then 40V; thereafter, we increased V_{IN} in 1V steps up to 50V while monitoring device current and output voltage V_{OUT}.

In total, eleven devices were tested, most of them at ambient temperature and 0 degree incident angle. We did perform 60-degree angle and elevated temperature (70°C) measurements as well. The test board and the DUT are shown in Fig. 2.

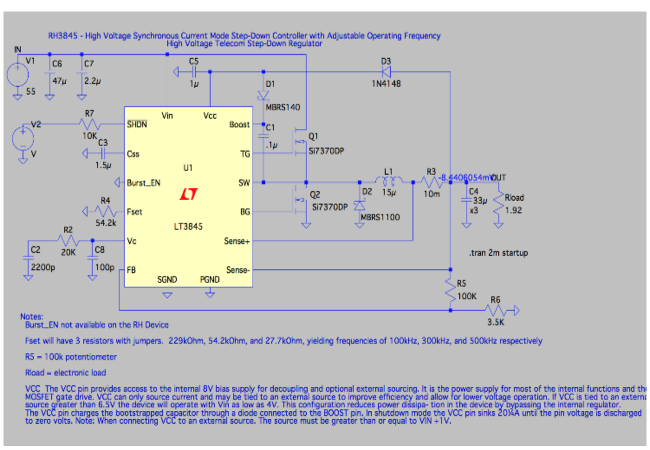

Fig 1. Schematic of the test board for RH3845/LT3845.

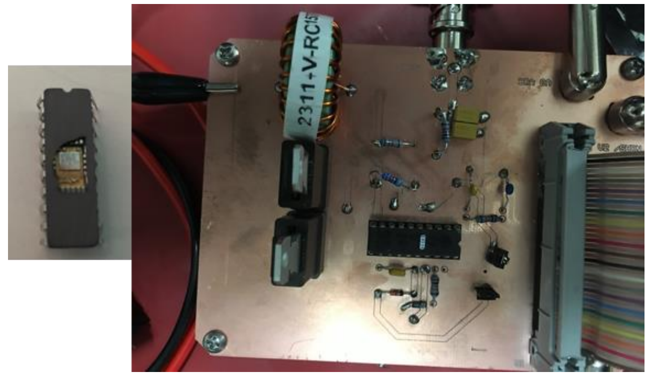

Fig. 2. The decapsulated DUT and the test board with 20-DIP socket.

2) ISL78843ASRH

For both the heavy ion and laser measurements, the Intersil ISL78843 was tested using closed loop evaluation board provided by Intersil; the schematic can be found in the Intersil radiation report [8]. The aim was to follow Intersil's test procedure as closely as possible. The devices were irradiated to a fluence of $1\text{x}10^{7}$ cm^{-2} or 100 events, whichever occurred first. The supply voltage (V_{DD}) was varied from 12V to 14V at 0.5V steps, and then increased to 14.7V. The supply current, which was being monitored at all times, was about 2 mA while the device was operating. The current threshold for SEL detection on the power supply software was set to 10 mA while irradiating. The part was irradiated at room temperature and at elevated temperature of about 125°C. Device functionality was monitored at all times through the driver output (OUT) pin. The evaluation test board in front of the TAM cyclotron beam is shown in Fig. 3.

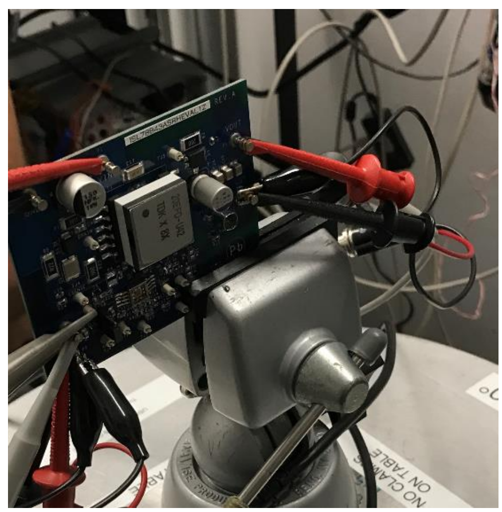

Fig. 3. ISL78843 closed loop evaluation board used at TAM.

C. Test Setup

The following general test setup was used for all the experiments. A four-channel Agilent N6700B power supply was placed and connected to the nearby DUT. The power supply is controlled and monitored through our custom PC software connected through an Ethernet cable. Multiple scopes (Picoscope and Agilent MSO7104B) were also placed and connected to the nearby DUT for monitoring output voltages and functionality of the device. The scopes connect to our PCs through Ethernet and USB cables. An electronic load (HP 6060B) was also used for some portions of the experiment. An Agilent 34970A data acquisition unit was used for temperature monitoring through Keysight's BenchVue software and the attached thermocouples. A heat gun and resistive heating strips were used for elevating the DUT temperature. During every experiment, all ESD precautions were taken and all up-to-date calibration dates for the following equipment were noted as well. A simplified and generic diagram of the test setup is shown in Fig. 4.

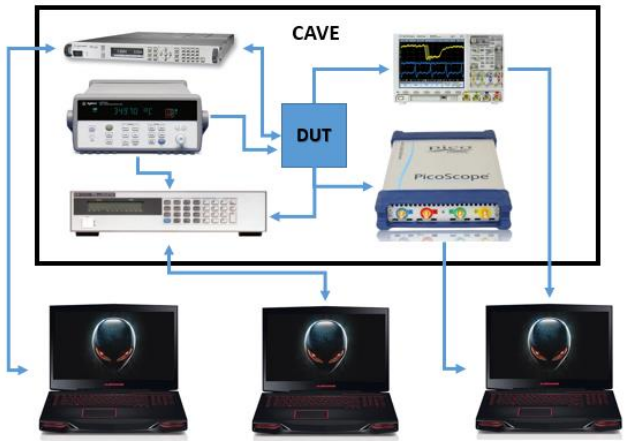

Fig. 4 Test setup with all the instruments and equipment used for testing.

IV. Test Results and Discussion

A. RH3845

Destructive SEE were observed when the input voltage was greater than 40V. A typical test run is shown in Fig. 5 where V_{IN} is increased while monitoring device current and V_{OUT}. The device exhibited destructive SEE when V_{IN} was at 50V. The quantity V_{SEE} was defined as the average for the last pass and failure voltage for the device, or 45V for Fig. 5. The error bars are one-half of the difference; therefore, it is 5V for Fig. 5. Later runs were done with smaller voltage steps to determine V_{SEE} more precisely. V_{SEE} is plotted as a function of LET in Fig. 6 for the parts tested, and the cross-section is plotted as a function of LET in Fig. 7. Fig. 8 presents pictures of the die showing the failure region. Both the V_{IN} and local ground wire were blown off the die.

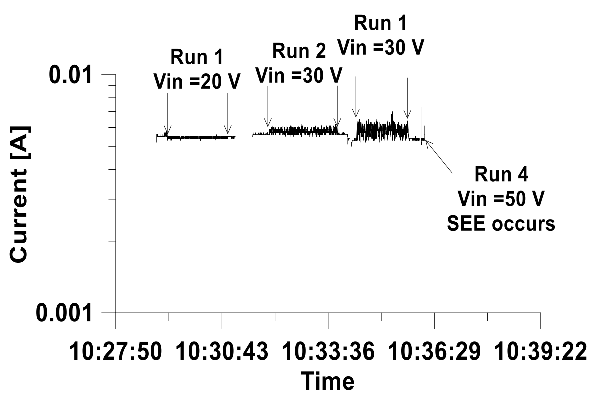

Fig. 5 A typical test run showing the determination of the V_{SEE} value for a device. V_{SEE} is 45V with error bars of 5V for this specific run. Later runs were done with smaller voltage steps to determine V_{SEE} more precisely.

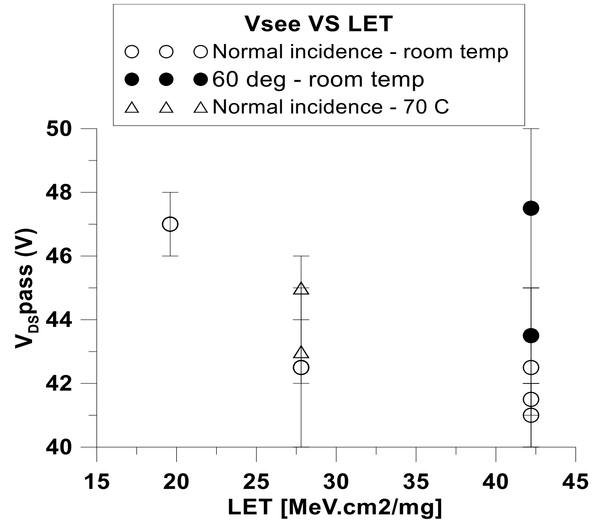

Fig. 6 V_{SEE} as a function of LET for various testing configurations.

The results of the testing are shown in Table III. The destructive SEE may be described as single-event dielectric rupture (SEDR) since it is a hard error that causes micro-damage in the device; however, we are making no claims to the specific mechanism. The potential SEDR was observed above 41V. Voltage cross-section did improve with elevated temperature and angle. The device is immune to SEL and SEU up to 77 MeV-cm^2/mg. The device showed no residual effect from the heavy ion radiation. Independent testing was also performed by the manufacturer around the time of the writing of this abstract. The results agree well with those presented in this paper.

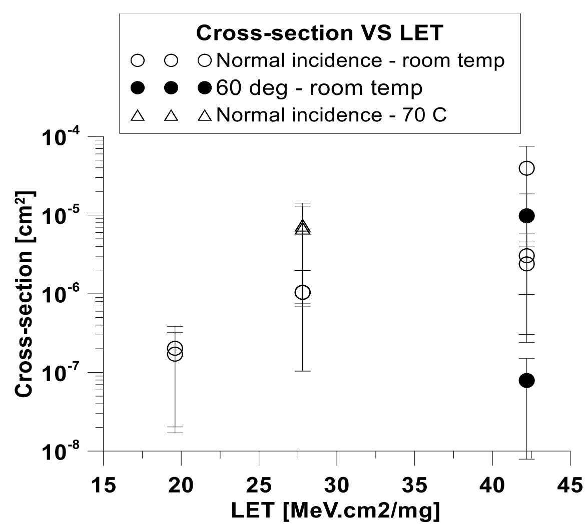

Fig. 7 Cross-section as a function of LET for various testing configurations.

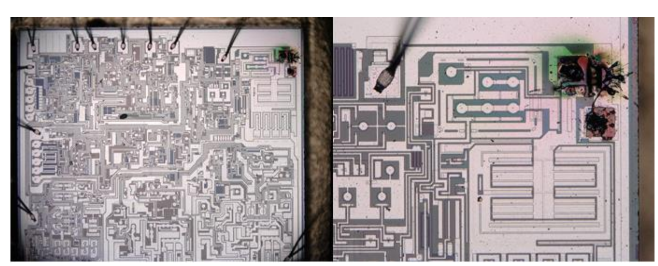

Fig. 8 Photomicrographs of a RH3845 that exhibited destructive SEE.

TABLE III
RH3845 SEE test results.

Device	**SEDR Threshold ($MeV\text{-}cm^2/mg$)**	**SEDR Saturation Device Cross-section (cm^2)**
RH3845	< 20	1×10^{-5}

B. ISL78843ASRH

Given the high-current events published in the Intersil test report, we first verified the room temperature response using a 15 MeV/amu Ag ion and increased V_{DD} starting at 12, 12.5, 13.0, 13.5, 14.0 to 14.7 V. Once we verified the part passed at room temperature, the test was repeated for a temperature of 125°C. During irradiation, with the device bias set to a minimum of 12V and elevated temperature, the current draw of the part jumped from a few milliamps to 40mA. We paused the beam and attempted to clear the current increase, but the only way to clear the increase was to lower voltage below a consistent holding voltage.

We repeated the measurement for several runs over three different devices. We observed the same current increases to about 40mA, but in every instance, if we continued irradiating the part, the high-current event cleared, introducing doubt to the mechanism inducing the current event. In order to determine the underlying cause, we repeated the test at JPL's picosecond laser system.

The test conditions were replicated on the laser system. With V_{DD} biased to 14.7V and temperature set to 125°C, the two sites exhibited the same current latch event. Those locations are shown on the die micrograph in Fig. 9 (red arrows). Once we induced the high-current event, the second location where the high-current event was cleared was discovered and shown in Fig. 9 as well (green arrow) [8].

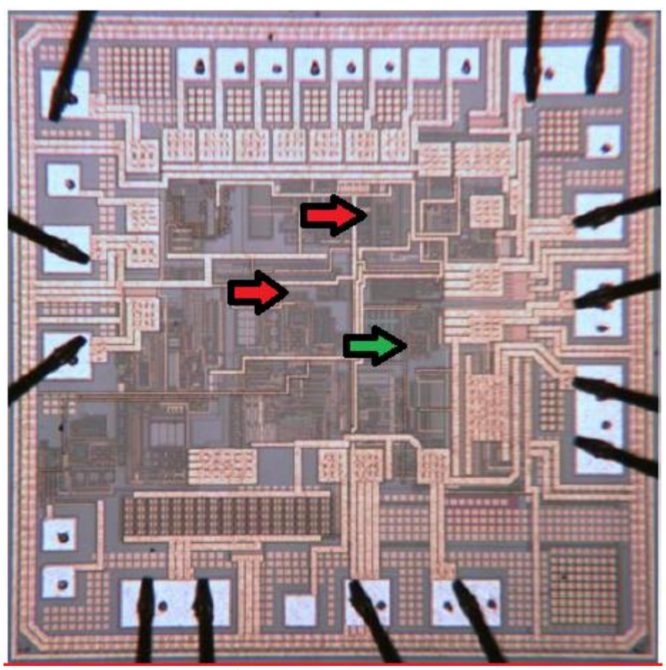

Fig. 9 Photomicrograph of the entire ISL78843 die with latchup sites (red arrows) and the latchup clear site (green arrow) marked [8]. Die photo released with explicit permission from Intersil Corporation.

We verified with Intersil that the locations we identified leading to the latchup events under laser exposure consist of an abutment of NMOS and PMOS devices. These structures provide the classic NPNP SCR construction for CMOS circuits that can lead to latchup. The ion or laser triggers the SCR which then latches ON and leads to the excess current condition. The recover location (green square and dots) is the under-voltage circuit for the voltage supply to those latching structures. Intersil asserts that the recovery event is the interruption of the voltage supply to the latched structures. Thus, the event at the recovery location simulates a power-down situation at the latching locations and leads to recovery [9].

V. Conclusion

Two radiation-hardened switching regulators were tested in a heavy-ion broad beam and JPL's laser system; they both exhibited destructive and potentially destructive SEE respectively [10]. In the case of the RH3845, a mechanism is still being determined so that the appropriate voltage derating can be applied as applicable. In the case of the ISL78843ASRH, the mechanism was identified as SEL, which was only observed at elevated temperatures with a $LET_{TH} > 76.5$ MeV-cm^2/mg.

References

[1] RH3845MKDICE Landing Page: http://www.linear.com/product/RH3845MKDatasheet Linear
[2] MSK5055RH Landing Page: http://mskennedy.com/products/Switching-Regulators/MSK5055RH.prod
[3] Intersil ISL7884X Landing Page: http://www.intersil.com/en/products/space-and-harsh-environment/rad-hard-power/rh-switching-controllers/ISL78840ASRH.html.
[4] Texas A&M Cyclotron webpage, http://cyclotron.tamu.edu, July 2008.
[5] JPL SEE Picosecond Laser Facility, webpage, http://parts.jpl.nasa.gov/organization/group-5144/jet-propulsion-laboratorys-single-event-effects-picosecond-laser-lab/
[6] ASTM F1192M-95 "Standard Guide for the Measurement of SEP Induced by Heavy Ion Irradiation of Semiconductor Devices," ASTM, 1919 Race St., Philadelphia, PA 19103.
[7] JEDEC JESD57, "Test Procedure for the Management of Single-Event Effects in Semiconductor Devices from Heavy Ion Irradiation (JC 13.4)," EIA/JEDEC, 2500 Wilson Blvd., Arlington, VA 22201-3834.
[8] ISL7884X Radiation Test Report, "Single Event Effects (SEE) Test Report for ISL78843ASRH and ISL78845ASRH High Performance Single-ended Current Mode PWM Controllers," http://www.intersil.com/content/dam/Intersil/documents/isl7/isl7884xasrh-see-test-report.pdf
[9] Private email with Larry Pearce of Intersil Corp., January 10, 2017.
[10] H. N. Becker, T. F. Miyahira and A. H. Johnston, "Latent damage in CMOS devices from single-event latchup," in IEEE Transactions on Nuclear Science, vol. 49, no. 6, pp. 3009-3015, Dec 2002.